# Technology Development for the Space Interferometry Mission (SIM)

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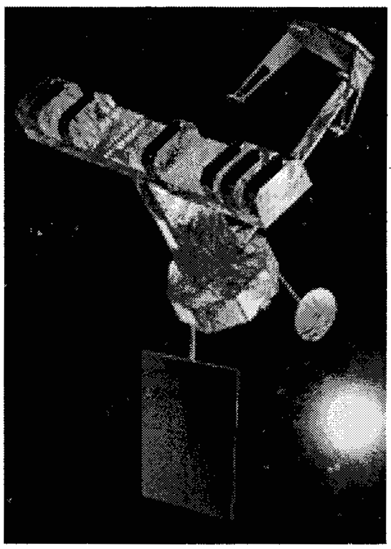
*Abstract*–Optical and infrared interferometry will open new vistas for astronomy over the next decade. Space based interferometers, operating unfettered by the Earth's atmosphere, will offer the greatest scientific payoff. They also present the greatest technological challenge: laser metrology systems must perform with sub-nanometer precision; mechanical vibrations must be controlled to nanometers requiring orders of magnitude disturbance rejection; a multitude of actuators and sensors must operate flawlessly and in concert. The Interferometry Technology Program at NASA's Jet Propulsion Laboratory is addressing these challenges with a development program that plans to establish technology readiness for the Space Interferometry Mission by early in the year 2001.

## 1. Introduction

The Space Interferometry Mission (SIM), with a target launch date of June 2005, will be one of the premiere missions in the Astronomical Search for Origins (ASO) Program, NASA's bold endeavor to understand the origins of the galaxies, of planetary systems around distant stars, and perhaps the origins of life itself. This adventure of discovery will be enabled by an explosive growth of innovative technology, as exciting in its own right as the underlying scientific quest.

Over the past several years a consensus has formed around the idea that space based optical interferometers operating in the visible and infrared wavebands represent the next great leap forward in astronomy and astrophysics. Interferometers lend themselves to space application due to their extremely efficient use of weight and volume to achieve the goals of high resolution, high sensitivity imaging and astrometry. SIM will mark NASA's first scientific use of this revolutionary observing technique in space. If it succeeds, it will presage the flight of the Terrestrial Planet Finder (TPF) and other larger and more ambitious Origins interferometers.

It is not surprising that such a huge step forward in observational power requires a concommitant leap in technological sophistication. SIM indeed drives the state-of-the-art in optomechanical and optoelectronic systems as well as presenting daunting challenges in precise stabilization of lightweight deployable structures and coordinated computer control of numerous optical surfaces. In this sense it very much embodies the principles of the Origins program -- to couple breakthrough science with breakthrough technology in the service of both a fuller knowledge of our universe and a



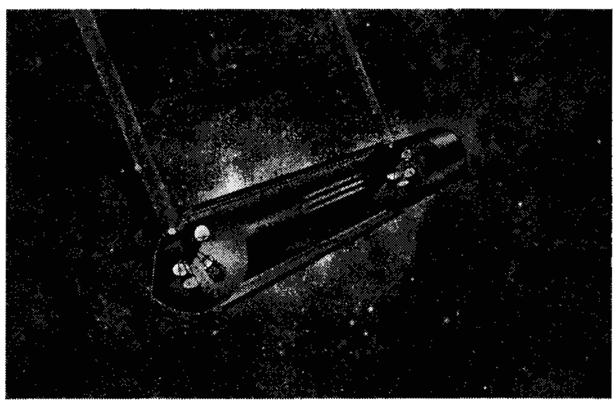


Figure 1 SIM Candidate Architectures

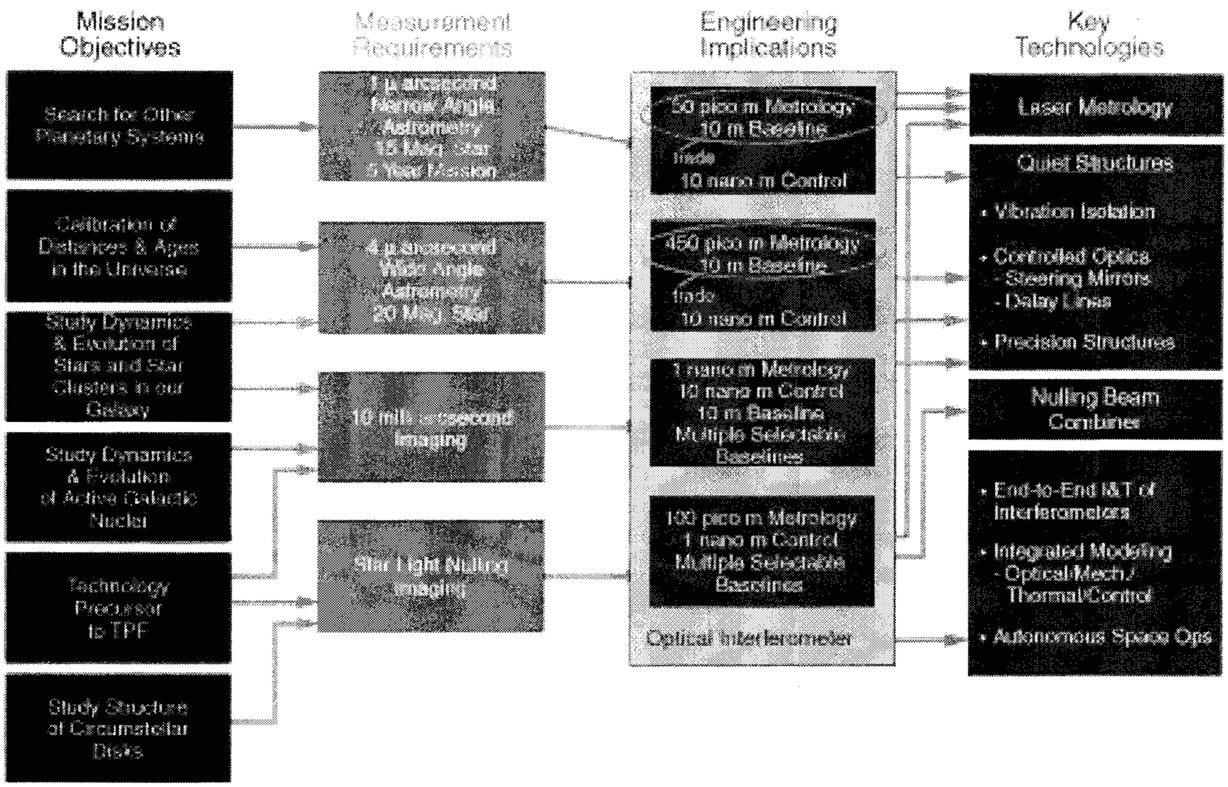



Figure 2 SIM Technology Requirements Flowdown

richer technological landscape that helps preserve our nation's preeminence as a force for global innovation. In this regard technology has become an important end-in-itself for NASA's Origins missions.

### *Major Technical Challenges*

Figure 1 depicts artist renditions of the two lending architectures for SIM. Successful development of either requires that three grand technological challenges be met and overcome:

(1) nanometer level control and stabilization of optical element on a lightweight flexible structure

(2) sub-nanometer level sensing of optical element relative positions over meters of separation distance

(3) overall instrument complexity and the implications for interferometer integration and test and autonomous on-orbit operation.

These flow from the fundamental science objectives of the mission, as illustrated in Figure 2.

The need for nanometer control is driven by requirements on fringe visibility for astrometry and imaging as well as by the requirement for $10^4$ starlight nulling. The nulling requirement is the more stringent necessitating 1 nanometer RMS optical path difference (OPD) control over a broad frequency range. Fringe visibility requirements translate into the need for 10 nanometer RMS OPD control.

The picometer regime metrology requirements flow directly from the principal astrometry science requirements. In order to make a 4 microarcsecond angular measurement between two stars using a 10 meter baseline triple interferometer requires the relative measurement of baseline positions to 100 picometers.

The complexity of an interferometer, with all its moving parts and control systems, is the price that must be paid for stepping beyond the paradigm of rigid monolithic telescopes as built since the days of Galileo. SIM will have to use active feedback control for at least 50 optical degrees of freedom. Another 80 degrees of freedom will need to be controlled in open loop fashion. Additional degrees of freedom will require articulation at least once for initial deployment and instrument alignment. All of this places great importance on the development of realtime software capable of autonomously operating SIM. New and creative integration and test methods will also be required to enable development of the instrument at an affordable cost.

The suite of new technologies that must be developed to enable SIM is depicted in Figure 3.

*Technology Development Approach*

Fundamentally the approach taken to technology development is one of rapid prototyping of critcal hardware and software followed by integration into technology testbeds where critical interfaces can be validated, system level performance demonstrated, and integration and test procedures developed and verified. To some extent, due to the objective of completing the technology development by the end of FY'01, this will entail concurrent engineering (e.g., we will need to develop some hardware component brassboards in parallel with the development of the testbeds, dictating that breadboards of those components will be used in the testbeds rather than brassboards, which would be preferred).

This approach places the ground testbeds at the very heart of the technology development effort. It is in these testbeds that the technology products will be validated and technology readiness demonstrated. It is also in these testbeds that our engineering team will learn about what works and what does not when it comes to integrating and testing interferometers. Flight experiments will in general be undertaken only where the space environment is required to explore the relevant phenomenology.

*Component Hardware Development*

Breadboards and brassboards of the new technology components required by SIM will be built and tested by the technology program. The objectives are threefold: mitigate technical, schedule, and cost risk associated with key hardware components early in the SIM project life cycle (when the cost of correcting problems is low); deliver necessary components to the technology integration testbeds; transition the capability to manufacture the components to industry.

For each component to be brassboarded, whether it is built in-house, built in partnership with industry, or procured in a traditional manner, a series of performance and environmental tests will be conducted whose objective it is to qualify the component design as ready for space flight. A distinction is made between qualifying the design and qualifying the component itself. None of the brassboard components are destined for flight and hence the qualification process will lack the formality (and cost) associated with flight hardware. Nevertheless the qualification process will be quite rigorous with each component subjected to full functional, shock, random vibration, and thermal (and/or thermal / vacuum) testing. JPL quality assurance and reliability personnel will be included from the outset to ensure proper test procedures. Note that only those components considered as high risk will be built and tested as brassboards. Figures 4 and 5 depict examples of two units, the optical delay line and the astrometric beam combiner, that have finished development, performance and environmental testing.

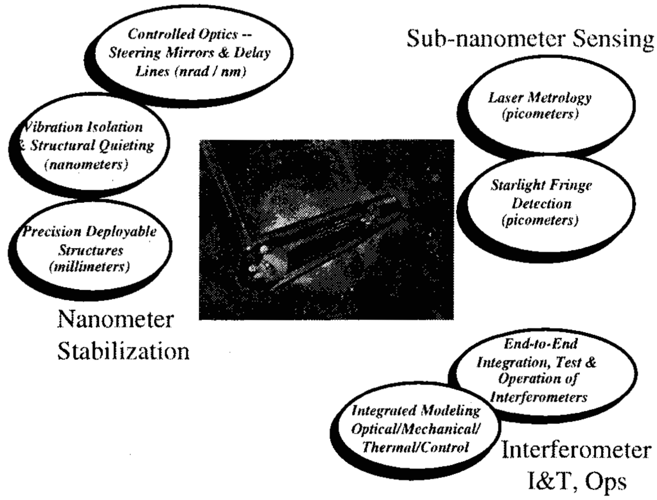



Figure 3 Key Technologies for SIM

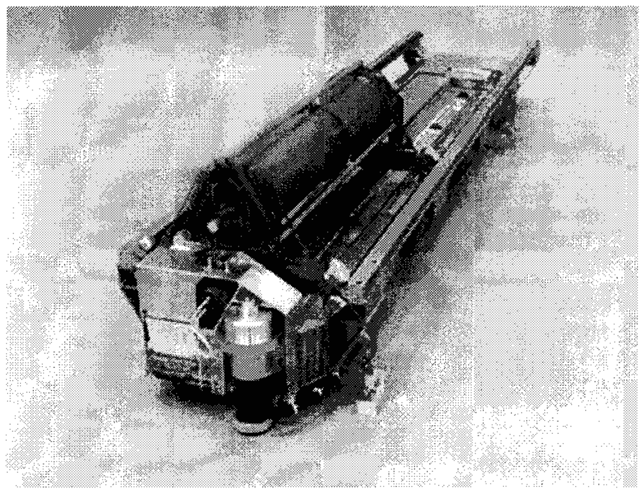


Figure 4 Brassboard Optical Delay Line

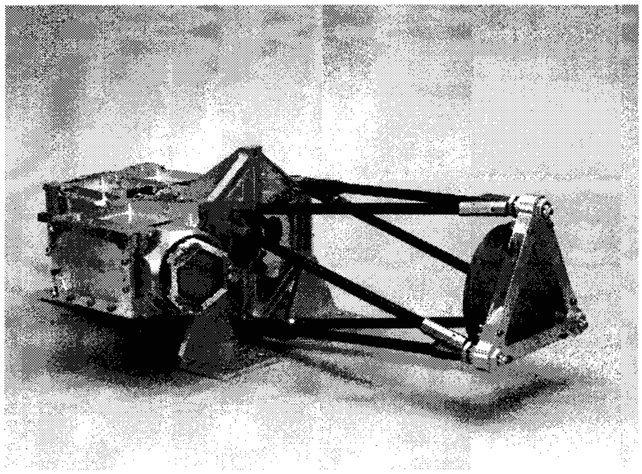


Figure 5 Brassboard Astrometric Beam Combiner

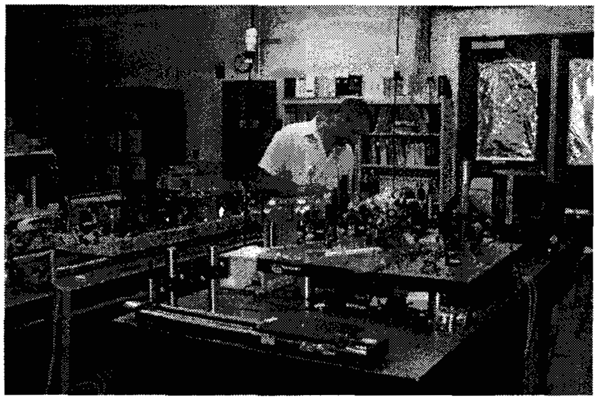


Figure 6 RICST Lab Hardware-in-the-Loop Testing

*Prototype Realtime Software Development*

Space interferometers will be required to operate with limited intervention from the ground and in doing so perform initial optical alignment, calibration, stellar target acquisition, angle tracking, fringe tracking, slew, continuous rotation for synthesis imaging, and other autonomous functions. Realtime software will play the central role in performing these functions. This software represents a significant technical challenge since it will have to operate a very complex instrument, run on a distributed set of computers, and control processes at timescales from milliseconds to days. As advanced systems demand increasingly sophisticated software, the portion of project cost (and associated schedule and cost risk) assigned to software begins to rival that of hardware. Hence, the technology program has determined to place the importance of the development of realtime software on a par with that of interferometer hardware.

The approach to realtime software development is completely analagous to the development of component hardware via breadboards and brassboards. "Breadboard" software is regarded to be code that establishes the feasibility of performing a particular function. "Brassboard" software is a true prototype of flight software and demonstrates that the constraints imposed by the target flight processor can be met and that the code is efficient and maintainable. It is intended that the brassboard (or prototype) software developed under the technology program could actually be flown on SIM with only minor modification and upgrade required.

The job of developing SIM breadboard software is largely already done thanks to the development of two ground interferometers in recent years: the Palomar Testbed Interferometer (PTI) and the Micro-Precision Interferometer (MPI) Testbed PTI and MPI share a significant amount of common realtime software and together demonstrate the basic feasibility of automated interferometer operation.

The development of the SIM prototype (or brassboard) software will take place in a development environment called the Realtime Interferometer Control Software Testbed (RICST). RICST will build the code in a modular fashion and will make a series of incremental deliveries. This will greatly simplify the process of testing and debugging. The initial deliveries will be internal to the RICST team and will serve to validate the development approach and train the personnel. RICST testing will incorporate breadboard and brassboard hardware allowing the software to be fully exercised by actually driving the relevant controlled components (Figure 6). Eventually, the RICST software will be delivered to integration testbeds (described below) where it will be used to operate complete interferometers like SIM. This process is expected to result in software that can be referred to as "protoflight" -- ready for flight application with modest rework.

*Integrated Modeling Tool Development*

The challenges facing space interferometry do not lie exclusively in the province of developing component hardware and realtime control software. Work is also needed to advance the state-of-the-art for software tools for analysis and design. Existing analysis tools provide only limited capability for evaluation of spaceborne optical system designs. They determine optical performance from the geometry and material properties of the optical elements in the system, assuming only minor deviations from the nominal alignment and figure. They cannot evaluate the impact on optical performance from controlled/articulated optics, structural dynamics, and thermal response, which are important considerations for future interferometer missions. To investigate these critical relationships, a new analysis tool has been developed called Integrated Modeling of Advanced Optical Systems (IMOS). IMOS enables end-to-end modeling of complex optomechanical systems (including optics, controls, structural dynamics, and thermal analysis) in a single seat workstation computing environment. IMOS has been applied at JPL to the Hubble Space Telescope and the Space Infrared Telescope Facility (SIRTF), as well as virtually all the space interferometer designs that have been considered in recent years (e.g., SIM, OSI, ISIS, SONATA, DLI, FMI, MPI, POINTS).

IMOS was originally created as a modeling tool to assist in the early design phases of multidisciplinary systems. In recent years IMOS has matured tremendously and has greatly increased its ability to address complex, many degree-of-freedom systems that are typical of the detail design phase. Currently IMOS is the baselined integrated modeling tool for the SIM project and NGST pre-project, and is also being adopted by their industrial partners. Figure 7 shows a thermal/mechanical analysis run in IMOS predicting the deformation of one of SIM's collector telescopes over expected temperature changes.

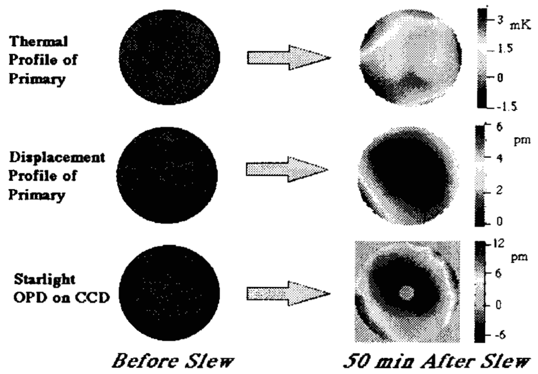



Figure 7 Collector Deformation Map Over Termperature

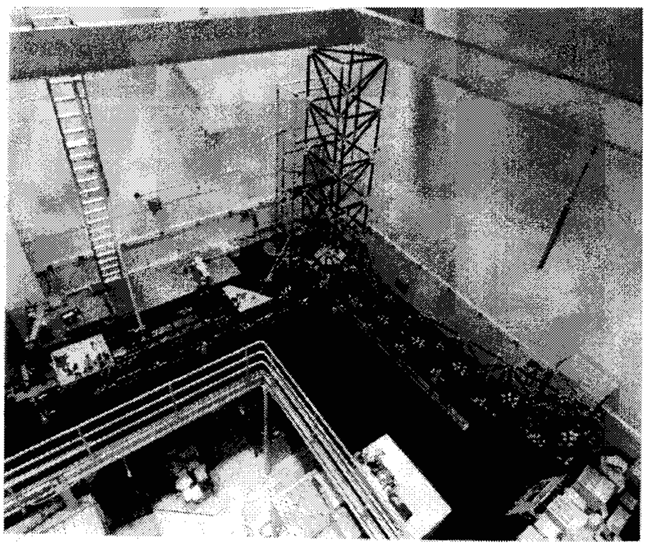


Figure 8 Bird's Eye View of STB-1

## *Ground Integration Testbeds*

In some sense the hardware and software products delineated above comprise the full set of tools and parts that the SIM Project needs to design, build and operate the interferometer instrument. However, having developed all the pieces, one huge task remains to be done -- proving that they all fit together and work as an interferometer at the relevant levels of performance. This is the province of the ground testbeds.

Three major ground testbeds are planned: the evolutionary SIM System Testbed (STB-1,3), the Microarcsecond Metrology (MAM) Testbed, and the Palomar Testbed Interferometer (PTI). This particular delineation of the ground testbed effort derives from the recognition that one major subset of the technologies can be tested in air at nanometer precision and at full scale while another subset must be tested in vacuum at picometer precision but at subscale. The first set of technologies, i.e. those associated with vibration attenuation, is grouped into the STB-1,3. The second, i.e. the laser metrology technologies, is assigned to the MAM Testbed. PTI, an operational ground based interferometer observatory, is unique in that it is capable of viewing real stars which is necessary to validate the science data processing software.

*SIM System Testbed (STB)*–The SIM System Testbed is actually an evolutionary series of two testbeds. The first, STB-1, was built during the FY'91 through FY'94 timeframe. It is a full single baseline interferometer built on a flexible structure (see Figure 8) out of breadboard hardware components.

The structure is a 7m x 6.8m x 5.5m aluminum truss weighing 200 kg (with optics and control systems attached the weight is about 600 kg). Three active gravity off-load devices make up the structure's suspension system providing about a factor of ten separation between the structure's "rigid body" and flexible body modes (the lowest of which is at about 6 Hz). The equipment complement includes a three tier optical delay line with associated laser metrology, a pointing system complete with two gimballed siderostats, two fast steering mirrors, and coarse and fine angle tracking detectors, a six-axis isolation system, and all associated electronics and real time computer control hardware necessary for closed loop system control and data acquisition. The principal objectives of STB-1 are demonstrating vibration attenuation technologies and validating the IMOS modeling tool in the nanometer regime. STB-1 was completed during the summer of 1994 when "first fringes" were acquired. Two metrics have been tracked over time to monitor testbed progress. These are: (a) pseudo-star fringe tracking stability in the presence of the laboratory ambient vibration environment and; (b) fringe stability vs emulated spacecraft reaction wheel disturbances, which are expected to be the dominant on-orbit disturbance source. The current performance, as measured by each metric, is below 5 nm RMS (see Figure 9 for a typical lab ambient fringe tracking time trace). Progress over time for these metrics is depicted in Figure 10. The goal is to achieve 1 nm by the end of the evolutionary STB program.

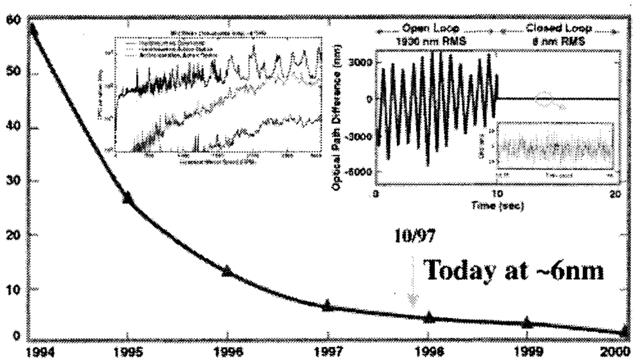



Figure 9 Time Trace of STB-1 Fringe Tracking OPD with Control Loops Open/Closed

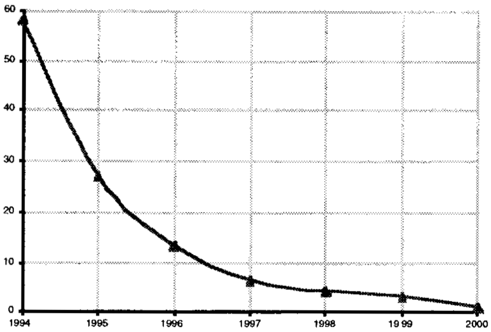



Figure 10 Historical Improvement in STB-1 Ambient and "On-Orbit" Metrics

STB-3 is essentially a new build from the ground up. The goal is to build a testbed whose operational complexity approaches that of the SIM flight instrument.

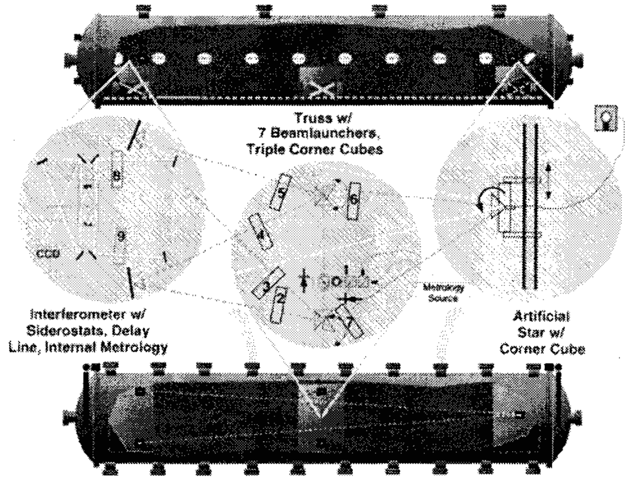



Figure 12 Microarcsecond Metrology (MAM) Testbed Configuration

## *Microarcsecond Metrology (MAM) Testbed*

The Microarcsecond Metrology Testbed will demonstrate that picometer metrology components can be configured with a stellar interferometer, per the approach of the SIM instrument, to enable the measurement of point source (viz, pseuso-star) position to the microarcsecond level. This will be done at one fifth scale in a 3-m x 13-m vacuum chamber (see Figure 11). The MAM Testbed uses a 1.8 m baseline interferometer to observe an artificial star. The positions of the star and interferometer are monitored by an external metrology system that allows one to calibrate the star position measured by the interferometer. The interferometer layout is shown in Figure 12.

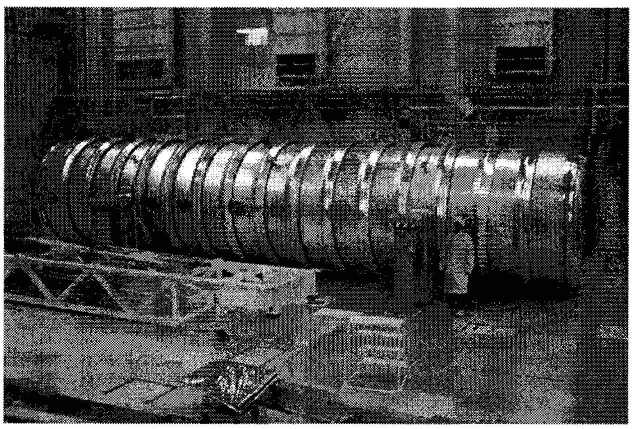


Figure 11 MAM Testbed Vacuum Tank Installed in JPL Highbay

The interferometer includes siderostats for wide-angle acquisition, fast steering mirrors for fine guiding, a delay line for optical path control, and a beam combiner with both imaging and single-pixel detectors. The metrology system consists of nine beam launchers; two that monitor the star, two that monitor each siderostat, one that monitors the external metrology "truss," and two internal launchers that monitor the optical path length through the interferometer. In this way, the metrology system is a 2-D version of the 3-D system proposed for SIM. The interferometer includes all of the functionality of SIM (except for switching mirrors), in a reduced scale and reduced dimensionality experiment. The MAM optics, metrology system, and artificial star are placed in a vibration-isolated, thermally stabilized, vacuum chamber. This eliminates index of refraction fluctuations in air and allows the experiment to achieve its goal of 50 pm optical path measurement accuracy.

Initial MAM operation is planned for late in 1999 with a single-baseline narrow-angle experiment. The artificial star will be moved over a 20 arcsecond (1 mm) range and its position will be monitored by both the white-light interferometer and the external metrology system. The experiment will attempt to show that it is possible to measure the position of the star to a few micro-arcseconds. The next stage of experimentation will be to increase the field-of-view (stellar motion), eventually reaching 1 degree. The controlled environmet will be perturbed by adding heaters and vibration transducers to key optical components. In this way one can study the interaction of dynamic effects on the calbration and operation of the interferometer.

The MAM testbed relies on the extensive use of picometer metrology laser gauges. These gauges are currently undergoing a series of careful tests to measure their performance. However, the fundamental feasibility of this laser gauge technology was experimentally demonstrated in the early 1990's. Heterodyne gauges were tested both in null gauge and relative gauge configurations. Figures 13 and 14 show that in both modes picometer level motions were successfully measured.

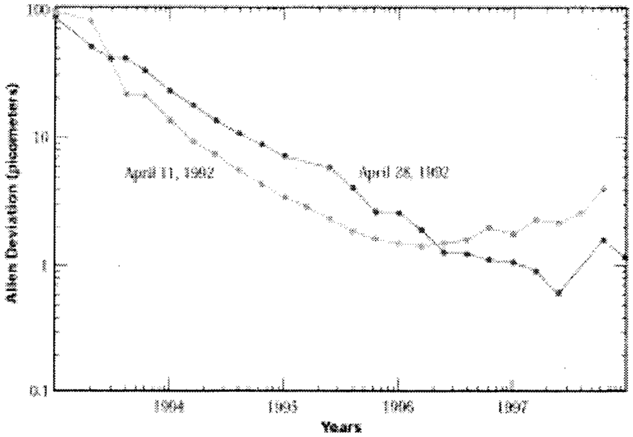



Figure 13  Allan Deviation Obtained with the Null Gauge

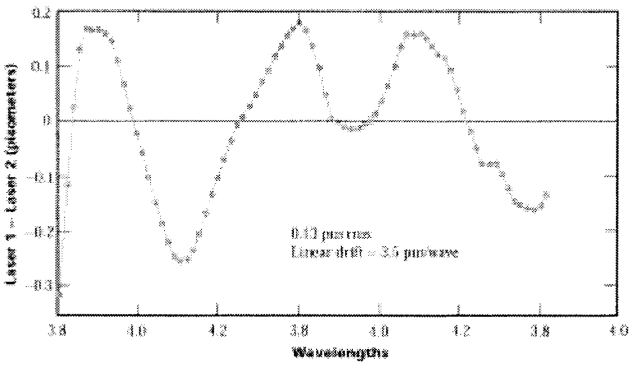



Figure 14  Results Obtained with the Relative Metrology Gauge

## *Ground Based Interferometer Observatories*

Ground interferometers are invaluable testbeds for space-based systems, not only from a hardware perspective, but also with a view toward operations and scientific productivity. Members of the JPL team have built and operated a series of ground interferometers over a period of nearly 20 years. These interferometers have pioneered advances in interferometer architecture, algorithms, performance, automation, and scientific productivity that are directly applicable to SIM.

The Mark I through Mark III interferometers were built and operated on Mt. Wilson and served as technological forerunners of the currently operational Palomar Interferometer Testbed (PTI). PTI was funded by NASA to demonstrate the technology for ultra precise narrow-angle astrometry. The ultimate application would be to the Keck Interferometer and the detection of exoplanets through observations of the perturbations of the parent star. Development of PTI began in December 1992, the site at Palomar Mountain was available for occupancy in May 1995, and first fringes were obtained three months later in July 1995. The instrument recently attained its performance goal of sub 50 mas narrow angle astrometry, at least over single observation times on the order of hours. Testing of multi-night astrometric measurement stability is currently under way. A photograph of PTI taken from the Palomar 5-m catwalk is shown in Figure 15.

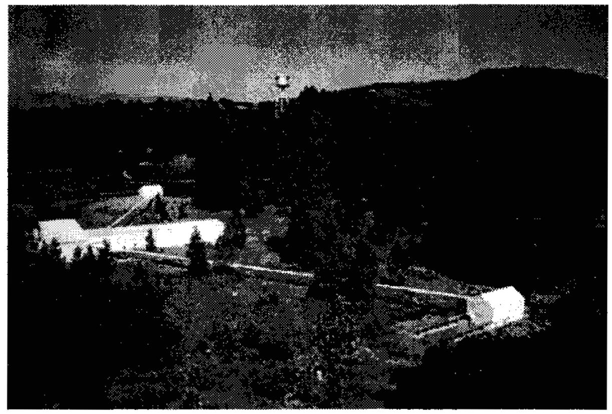


Figure 15  The Palomar Testbed Interferometer

PTI has a 110-m baseline, employing 50 cm siderostats with 40-cm telescopes. It is a dual-star system, using a bright target star to cophase the system in order to detect a faint astrometric reference star against which the astrometric perturbations of the bright target would be measured. PTI employs 4 delay lines, two with physical travels of 20 m each, and two with shorter travels for offsetting between the two stars. PTI, compared with the Mark I - III interferometers, works in the near-IR, and is the first infrared interferometer to employ the active-fringe-tracking technology originally developed on the Mark I. PTI also incorporates complete end-to-end laser metrology of the internal optical path from the stellar beam combiner to a corner cube located in front of the siderostat. This constant-term metrology system, to use the SIM nomenclature, uses the same optical architecture as proposed for SIM, employing the starlight beamsplitter as the metrology beamsplitter to eliminate non-common-mode measurement errors.

Perhaps the most significant benefit of PTI to SIM, besides the obvious one of building, integrating, and operating the instrument, is the implementation approach that was used. PTI was built in a highly modular manner, both with respect to the optical system and the computer control system. The computer system, which employs 9 real-time single-board computers, integrates these with a high-level communications architecture which hides most of the details associated with the large number of the CPUs from the subsystem developer. This allowed developers to concentrate on the details of their subsystem, and also allowed multiple developers to work simultaneously. Modularity allowed the testing of subsystems in the lab and on the roof of our lab at JPL, so that final systems integration on the mountain took less than 3 months to first fringes. PTI, while borrowing extensively from the Mark III, incorporated all new software (approximately 65k non-comment lines, of which 40k is the real- time control system). The modularity and testability of the architecture allowed a rapid development cycle. The architecture is also fairly autonomous. As a demonstration of the type of autonomy so necessary for the operation of space systems, PTI has been operated remotely from JPL, more than 100 miles away.

In the future PTI will serve as a development platform for interferometer science data processing software. Its narrow angle astrometry measurements are similar enough to those on SIM that the data processing software developed for the PTI astrometry will become the core of the SIM narrow angle astrometry science software.

Development of the Keck Interferometer (Figure 16) is taking place largely in parallel with the development of SIM technology. This has enabled synergistic work in at least two important areas: realtime software and starlight nulling. Keck and SIM will both make use of the same core software being developed by the RICST team. This should benefit SIM by virtue of having the luxury of seeing another operational system be the first to run the software though its paces. In the area of nulling, SIM and Keck have been able, thus far, to pursue a common nulling beam combiner development. Figure 17 shows the breadboard experimental set up that has been able to achieve, to date, better than a factor of 100 null on white light. This effort is now at the point of bifurcation where Keck must pursue hardware that operates in the infrared while SIM will build a visible light system. Nevertheless, the two efforts will continue to share results and learn from one another.

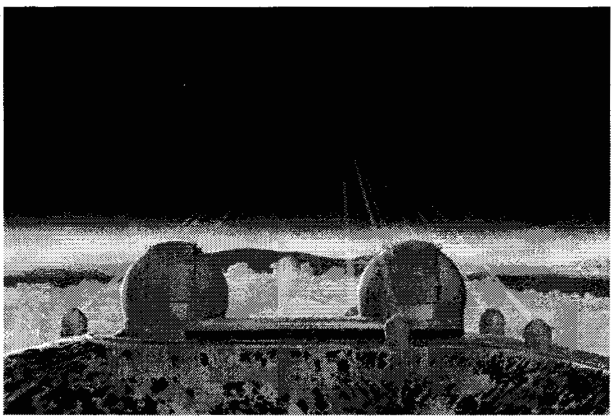


Figure 16 Artist's Rendition of the Keck Interferometer on Mauna Kea

### *Flight Experiments*

The philosophy that the Interferometry Technology Program takes toward flight experiments is to undertatke them only if the technology in question is one that cannot be validated via ground testing. The technology for deployable structures is considered to be relatively mature from the standpoint of scale (> 50 meter in length), initial

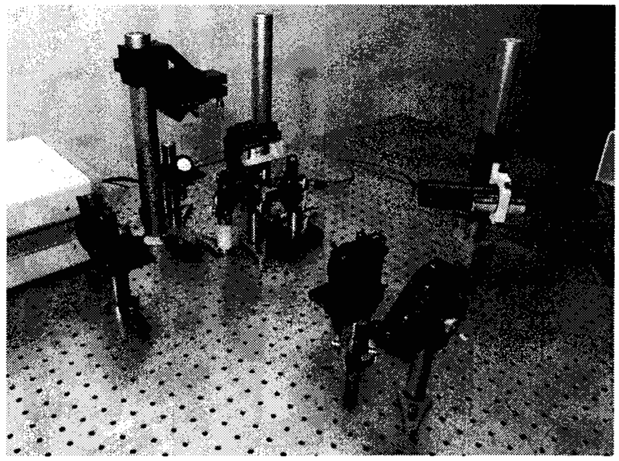


Figure 17 Nulling Beam Combiner Experimental Aparatus

deployment accuracy (millimeters), and long time scale stability over thermal loads (millimeters). On the other hand, the on-orbit short time scale stability (viz., above 1 Hz) of these systems in the nanometer regime is completely unknown. The concern is that deployable structures are dominated by hinges, latches, and joints all of which have the potential to exhibit stick-slip nonlinearities which are particularly susceptible to "creaking" due to time varying thermal conditions. Such creaking would be likely to have broad frequency content given its impulsive nature and hence, even if it occurs on the micron scale, could be quite problematic for an interferometer whose actively controlled optics might not have sufficient bandwidth to track it out.

Ground based experimental investigations into the microdynamic behavior of deployable structures is very difficult. In particular, testing in 1-g suffers from the inability to perfectly remove gravity induced internal loads from the test specimen in order to emulate on-orbit conditions. These gravity induced "preloads" could well act to completely hide the suspected stick-slip phenomena which would be unleashed only in space. This is the motivation for conducting space experimentation in order to understand the microdynamics of deployable structures.

IPEX-1 (Interferometry Program Experiment-1) was the first step toward filling the microdynamics information gap. Hosted on DARA's (German Space Agency) Astro-SPAS platform, which flew a shuttle sortie mission on STS-80 in December 1996, IPEX-1 gathered twelve channels of micro-g acceleration data using Sunstrand QA-2000 accelerometers sampled at 744 Hz. During quiet periods when thrusters were not operating, accelerations of the order of 100 micro-g's were measured. This data tells us two important facts: (i) the microdynamics of built up monolithic structures like Astro-SPAS appear compatible with interferometer mission requirements; (ii) the Astro-SPAS is a quiet enough platform to host future Origins flight experiments. The first of these, IPEX-2, was flown in August 1997, a scant eight months after IPEX-1. IPEX-2 (shown prior to flight in Figure 18 and on-orbit in Figure 19) consisted of an instrumented portion of a

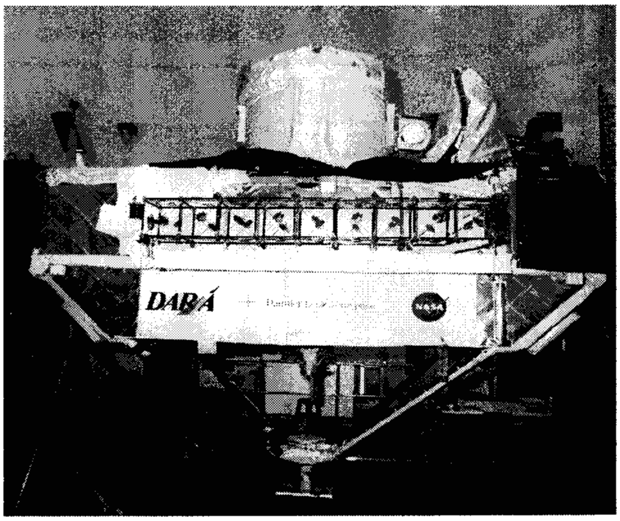


Figure 18 IPEX-2 Integrated to Crista-SPAS and Ready for Launch

representative deployable structure, a so-called ADAM-Mast built by ABLE Engineering of Goleta, California. IPEX-2 mission operations went perfectly. Over 60 channels of accelerometer, load cell, and temperature data were taken during various orbital thermal conditions including Sun-shade transitions and long duration hot and cold soaks. This voluminous data is currently being analyzed. However, the preliminary overriding conclusion is that deployable structures that are engineered to eliminate backlash in joints and placed in thermally benign orbits (e.g., Earth escape orbit like SIM's) will exhibit sufficiently low levels of microdynamics to support optical interferometry. The ultimate intent is to combine the flight data with ground test measurements to develop empirically validated analytical models capable of predicting the conditions leading to and the vibrations emanating from thermal creaks. This work will be carried out by JPL in conjuction with NASA LaRC and will involve university participation from MIT and University of Colorado.

### *Summary*

The technology necessary to make SIM a reality presents unprecedented challanges in the fields of nanometer stabilization, picometer sensing, and complex system integration, test, and autonomous operation. However, we are far from starting from scratch on this development effort. Work on these technologies--dispersed at first, now much more highly focussed--has been underway for almost 20 years. The "roadmap" of Figure 20 shows how the pieces described above fit together into a coherent whole. When this roadmap is followed to competion, sometime in 2001, SIM will be ready to begin flight system development with its formidable technical risks well understood and its critical technology in hand.

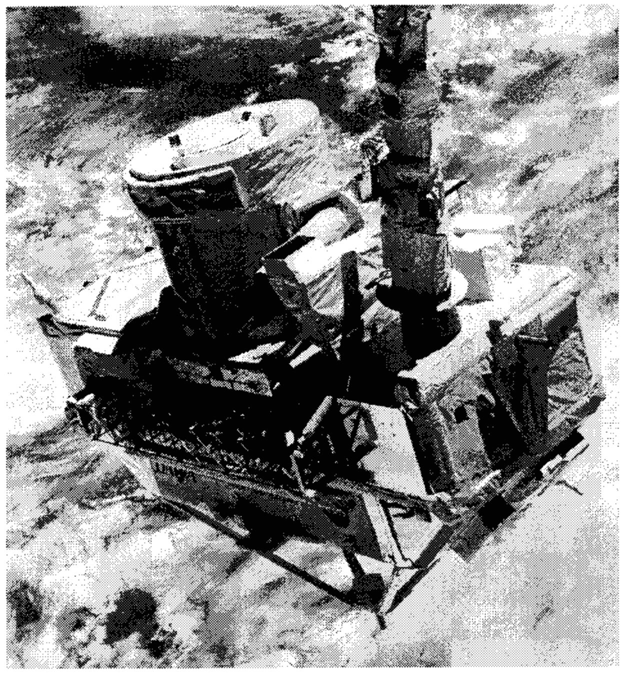


Figure 19 Crista-SPAS/IPEX-2 Deployment from Shuttle RMS

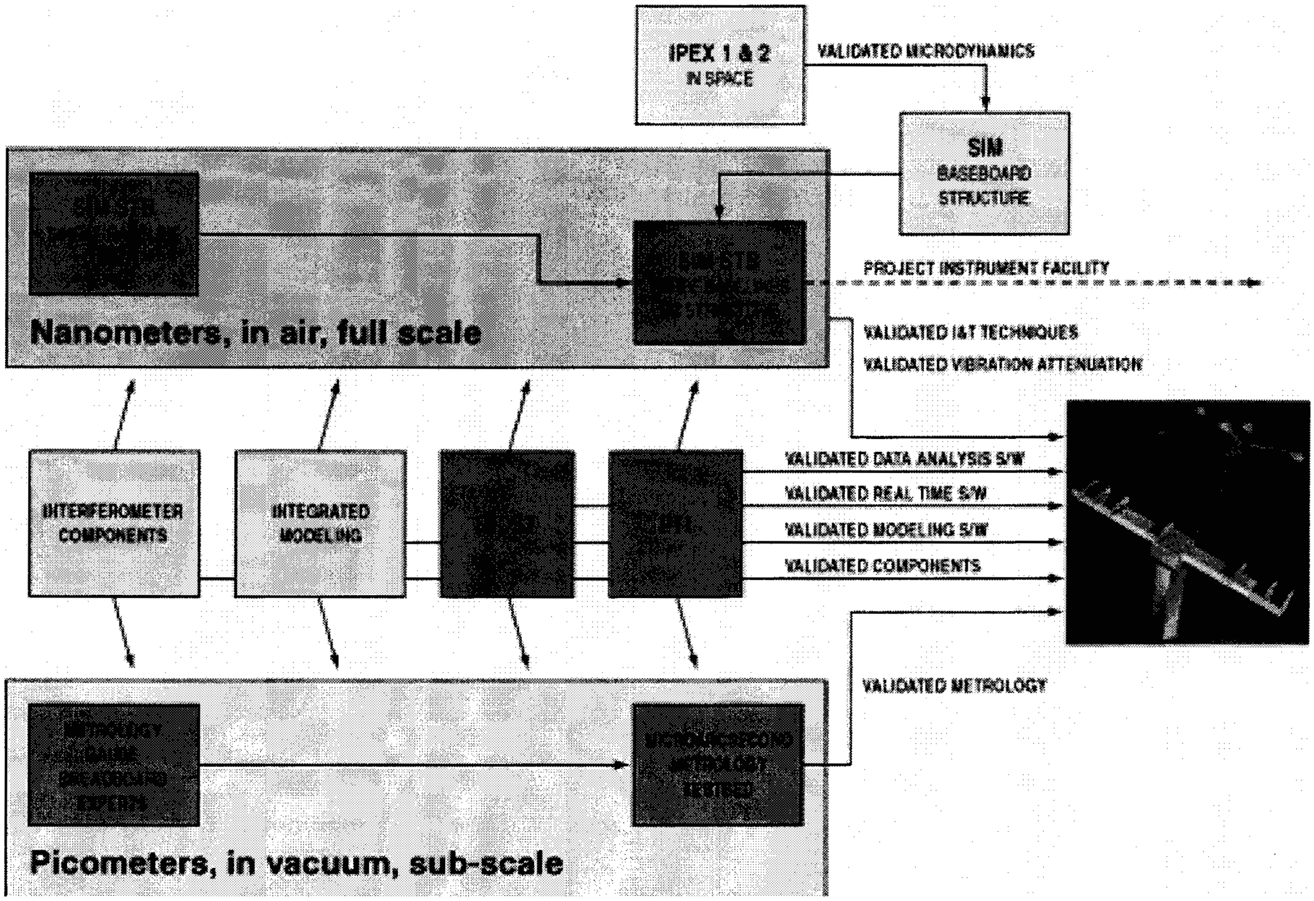



Figure 20 SIM Technology Development Flow

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## BIOGRAPHY

Robert Laskin is the project technologist for the Space Interferometry Mission (SIM). In this capacity he is responsible for developing the technology needed by SIM and keeping a watchful eye on the needs of future more ambitious space interferometers. Dr. Laskin received undergraduate degrees from Yale College (1974) and Columbia University (1978), a Masters from Stanford University in 1979, and the Ph.D. from Columbia in 1982, the latter three degrees all in mechanical engineering. Since graduating with his doctorate he has been with JPL, working largely on precision pointing, stabilization, and figure control of complex space optical systems. He joined JPL's Interferometry Technology Program in 1988 as system engineer and became program manager in 1991. He assumed his current responsibilities as SIM Project Technologist in 1997 when SIM officially became a project.

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